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DISPLACEMENT DAMAGE IN SILICON IRRADIATED WITH 6- TO 10-MEV NEU--ETC(U)
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MEMORANDUM REPORT NO. 2738

DISPLACEMENT DAMAGE IN SILICON IRRADIATED WITH 6- TO 10-MeV NEUTRONS

J. E. Youngblood
W. R. Van Antwerp
R. M. Tapphorn

April 1977

USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
USA BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Some preliminary experimental and theoretical results on the energy dependence of neutron-induced displacement damage in silicon are presented. The reduction in carrier lifetime, as reflected in the change in forward voltage at a fixed injection level, has been measured in wide-base silicon diodes, for monoenergetic neutrons at selected energies between 5.6 and 9.8 MeV. Twenty-five measurements at 19 energies were made. To calculate the variations in damage with neutron energy, a computer program that could utilize all details → next pg

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of the best available neutron cross section data was prepared. This program accepts coefficients for a Legendre polynomial fit of a partial cross section, determines the silicon recoil energy at a particular angle, and calculates the Lindhard fraction of energy for displacement damage. The calculated results provide a direct indication of the effect of angular distributions and the sensitivity of damage calculations to various details of the input neutron cross sections.

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I. INTRODUCTION

Permanent damage in silicon as a function of neutron energy has been studied extensively for several years. Experimentally, sufficient fluences of monoenergetic neutrons have been difficult to obtain and few results have been published for the energy range of 1.5 to 14 MeV. Theoretical calculations require a knowledge of the angular dependence of the various neutron cross sections, the appropriate reaction kinematics, and a suitable rule for partitioning the recoil energy into displacement and ionization fractions. The neutron total cross sections are now well known. Some of the various partial cross sections and their angular dependence are now available with sufficient accuracy for useful calculations; however, there are still rather large gaps in the available information in this area.

The results of Lindhard and coworkers[1], nominally verified experimentally by Sattler and Vook[2], can be used to partition the recoil energy into displacement and ionization components. These results on the partitioning of energy seem adequate, and the ionization effects are well understood. It is less certain that the displacement fraction is uniformly effective in producing permanent damage as reflected, for example, in degradation of carrier lifetime and in carrier removal.

The need for a rigorously determined curve which relates neutron energy and displacement damage, with its accuracy well specified, has been noted by Conrad[3]. Energy dependence of damage calculations are used both to correlate threat and test neutron spectra and to determine the damage equivalence of neutron spectra from various simulation facilities. The requirements for, and problems of, energy dependence have been analyzed by McKenzie and Witt[4] and by Van Lint, Leadon and Colwell[5]. Reference is made to these papers for discussions of the

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1. J. Lindhard, V. Nielsen, M. Scharff, and P.V. Thomsen, Mat. Fys. Medd, K. Dan. Vid. Selsk. Vol. 33, No. 10, 1963.
2. A.P. Sattler and F.L. Vook, "Partition of the Average Energy Deposited in Silicon as a Function of Incident Neutron Energy", Phys. Rev., Vol. 155, No. 2, pp 211-217, March 1967.
3. E.E. Conrad, "Considerations in Establishing a Standard for Neutron Displacement Energy Effects in Semiconductors", IEEE Trans. Nucl. Sci., Vol. NS-18, No. 6, pp 200-205, 1971.
4. J.M. McKenzie and L.J. Witt, "Conversion of Neutron Spectra to Their 14 MeV Equivalence", IEEE Trans. Nucl. Sci., Vol. NS-19, No. 6, 194-199, 1972.
5. V.A.J. Van Lint, R.E. Leadon, and J.F. Colwell, "Energy Dependence of Displacement Effects in Semiconductors", IEEE Trans. Nucl. Sci., Vol. NS-19, No. 6, pp 181-185, 1972.

existence of a general energy-dependence curve and the universality of such a curve. Also, it is beyond the scope of this report to discuss the relative merit of approximate damage curves such as those of Messenger[6]. These questions can best be addressed when a theoretical neutron displacement energy curve, proven by a detailed experimental evaluation, is available.

This memorandum report presents some preliminary experimental and theoretical results on energy dependence. Neutron induced displacement damage, particularly the reduction of carrier lifetime, has been measured in wide-base silicon diodes for monoenergetic neutrons at selected energies between 5.6 and 9.8 MeV. Twenty-five measurements at 19 different energies were made. The results were normalized to 14.2 MeV neutron damage and are nominally accurate, at least with regard to measuring the radiation-induced change, to 4%. The major uncertainty is that associated with the determination of neutron fluence.

To compare experimental results with calculations using the best available neutron cross section data, a computer program was prepared to accept coefficients for a Legendre polynomial fit of any angular distribution, determine the silicon recoil energy at a particular angle, and calculate the Lindhard fraction of energy for displacement damage. The program increments through 60, 3-degree intervals, finds the appropriate solid angle in each case, forms the product of the reaction cross section, recoil energy, displacement fraction, and solid angle, and sums the 60 contributions. Such an iterated calculation of damage is done approximately 15 times at each energy, covering all of the significant reactions. The calculated results provide a clear insight into the impact of angular distributions and the sensitivity of damage calculations to various details of the input neutron cross sections.

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6. G.C. Messenger, "Displacement Damage in Silicon and Germanium Transistors", IEEE Trans. Nucl. Sci., Vol. NS-12, No. 2, pp 53-74, April 1965.

II. BACKGROUND

Past experimental efforts on energy dependence include the work of Smits and Stein[7], Cleland et al.[8], Kantz[9], and Speers[10]. Studies of the energy dependence of neutron damage have been hampered by the problems associated with the production of intense beams of monoenergetic neutrons and accurate determination of neutron fluences. The clean monoenergetic neutron source available in the low-mass neutron room at the BRL Tandem Van de Graaff provided an ideal base for measurements. The present experimental work was undertaken using wide-base conductivity-modulated silicon diodes in a manner similar to Speers[10]. However, the change in forward voltage was observed 100 hours after exposure. With this technique, limited primarily by uncertainties in neutron fluence determination, one can make precise measurements when fluences are on the order of 10^{10} ncm^{-2} and thus it seems most appropriate for this application.

Until recently a detailed theoretical damage curve could not be generated because there was no correct theory for the fraction of recoil energy going into ionization. A sharp cutoff model proposed by Seitz and Koehler[11] was used through 1963, with a threshold energy above which only ionization occurred. Lindhard et al.[1], in 1963, developed a more realistic theory of energy partition. Modest calculations using this theory and including the effects of resonances and

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7. F.M. Smits and H.J. Stein, "Energy Dependence of Neutron Damage in Silicon-Experimental", Bull. Am. Phys. Soc., Vol. 9, No. 3, p 289, 1964. F.M. Smits, "On the Energy Dependence of Neutron Damage in Semiconductors", Sandia Report No. SC-R-64-196, 1964.
8. J.W. Cleland, R.E. Bass, and J.H. Crawford, Jr., "The Nature and Yield of Neutron-Induced Defects in Semiconductors", Conference on Radiation Damage in Semiconductors, Paris, 1964, Proc. of the 7th Int. Conf. on the Physics of Semiconductors, Vol. 3, Radiation Damage in Semiconductors, Paris-Royaument 1964, pp 401-406, Academic Press, New York, 1965.
9. A.D. Kantz, "Average Neutron Energy of Reactor Spectra and Its Influence on Displacement Damage", J. Appl. Phys., Vol. 34, No. 7, pp 1944-1952, 1963.
10. R.R. Speers, "Neutron Energy Dependence of Excess Charge Carrier Lifetime Degradation in Silicon", IEEE Trans. Nucl. Sci. Vol. NS-15, No. 5, pp 9-17, 1968.
11. F.Seitz and J.S. Koehler, "Displacement of Atoms During Radiation", Solid State Physics, Vol. 2, pp 307-448, Academic Press, New York, 1956.

fluctuations in the silicon cross sections have been reported by Smith et al.[12], Stein[13], and Holmes[14].

The calculations presented in this memorandum do not model the conversion of energy into damage but assume, in addition to the Lindhard partitioning of energy, that the permanent (and observable) damage is proportional to the energy available for displacements. However, the calculations are formulated so that all available details in the cross section input can be used.

Neither experimental nor theoretical damage evaluations can be done with the accuracy that total neutron cross sections have been measured. Nonetheless, it is important to try to relate calculations and/or measurements to the total neutron cross section. Figure 1 is illustrative of the current state-of-the-art in neutron total cross section measurements. From 6 to 7 MeV there are 125 points with an accuracy of 0.1% in neutron energy and of 3% in cross section value. This particular energy range was chosen to show the very large fluctuation found in the silicon total cross section. The extent to which the observed structure would be washed out by 100 keV-wide measurements is shown at two energies on Figure 1. These data are from an experiment done at the Karlsruhe cyclotron which covered the energy range from 0.5 to 30 MeV.

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12. E.C. Smith, D. Binder, P.A. Compton, and R.I. Wilbur, "Theoretical and Experimental Determinations of Neutron Energy Deposition in Silicon", IEEE Trans. Nucl. Sci., Vol. NS-13, No. 6, pp 11-17, 1966.
13. H.J. Stein, "Energy Dependence of Neutron Damage in Silicon", J. Appl. Phys., Vol. 38, No. 1, pp 204-210, 1967.
14. R.R. Holmes, "Energy Dependence for Carrier Removal and Lifetime Damage by Fast Neutrons in Silicon", Bell Telephone Laboratories Weapons Effects Studies, Report to ABMDA, Vol. II, Supplement III, pp 67-88, October 1, 1970.

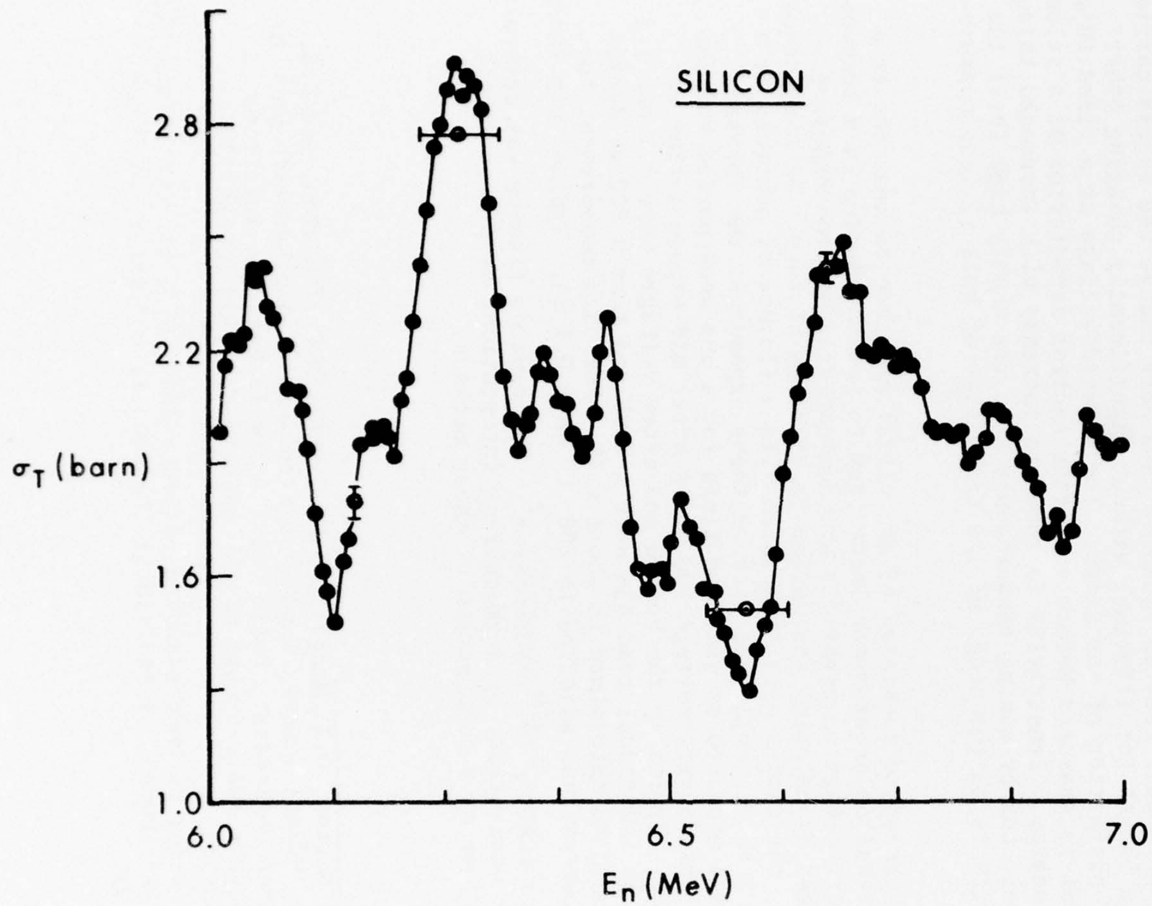

Figure 1. The Total Neutron Cross Section for Silicon from 6 to 7 MeV

III. EXPERIMENTAL TECHNIQUE

The experimental measurements of damage were made with wide-base, conductivity-modulated silicon diodes developed for Army use as a dosimeter[15]. Army interest in this application has, in fact, continued[16]. A diode is shown schematically in Figure 2. A p^+pn^+ or PIN structure is used and, by operating the diode at a fixed forward current (0.1A), a constant level of conductivity modulation is obtained. This is so because the modest neutron fluences used here change the excess carrier diffusion length (or lifetime) without significantly changing other physical properties of the diode. The forward voltage at a fixed injection level is measured before and after neutron irradiation at a selected neutron energy. Sensitivity is known to increase with increased injection level, and by making measurements at a reasonably high level the sensitivity is on the order of 100 times that of bulk silicon measurements.

The procedure consisted of an initial exposure to neutrons at a Cockcroft-Walton accelerator, necessary to put the diodes in a response range where damage observations are dominated by neutron exposure rather than by material and device-fabrication history. At a subsequent exposure, the diodes were irradiated with a fluence of neutrons at a selected energy. Following each of these exposures, the forward voltage was measured at selected times for a one week period and the value of the forward voltage 100 hours after mid-exposure-time was determined. Typically the before and after voltages were 1.1 and 1.2 volts. The individual readings were ± 2 mV and thus a 100 mV damage result could be determined to about ± 4%. For each measurement the forward current was adjusted to 100 .0 mA ± 0.1 mA. Typical exposures were approximately 10^{10} neutrons/cm^2. The neutron fluence was determined by sulfur activation, by beam-current integration, by proton-recoil telescope, or by a combination of these methods.

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15. H.C. Gorton, O.J. Mengali, J.M. Swartz, M.O. Thurston, and C.S. Peet, "Final Summary Report on Experimental and Research Work in Neutron Dosimetry: Phase III", Battelle Memorial Institute, 31 August 1961, Signal Corps Contract No. DA36-039-SC-78924, AD 265749.
16. Memorandum of Understanding, dated 1 June 1973, between US and UK, for Development of Individual (Personnel) Dosimeter, UK Diode VK-4509.

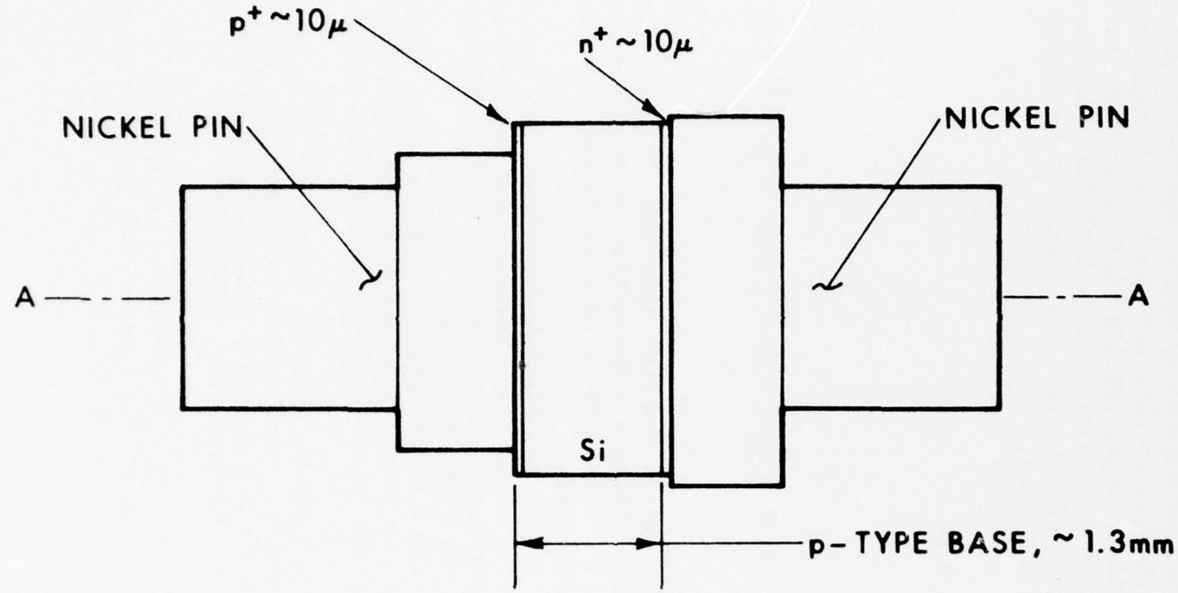

Figure 2. Silicon Diode Construction

Previous experimental studies of the wide-base diode have included evaluations of starting material[17], reverse-recovery lifetime[18], energy dependence[19], and annealing[20]. A theoretical analysis of the current-voltage characteristics of wide-based silicon diodes and the effects of neutron bombardment has been given by Swartz and Thurston[21]. These authors combine the changes in base and junction voltages at high level injection to obtain theoretical results that agree with the current-voltage characteristics of actual diodes, including neutron-exposure history. In the region of interest, the base voltage change with neutron irradiation will dominate, and:

$$\frac{1}{\tau} = \frac{1}{\tau_o} + K\phi \tag{1}$$

with

$$L = \sqrt{D\tau} \tag{2}$$

and

$$V_{base} = \frac{2kT}{e} \sinh\left(\frac{W}{2L}\right) \tan^{-1}\left[\sinh\left(\frac{W}{2L}\right)\right] \tag{3}$$

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17. J.M. Swartz, B.H. Chase, and M.O. Thurston, "Silicon Diode Fast Neutron Dosimeter - Phase I - Evaluation of Response Versus Starting Material", NDL-TR-83-I, US Army Nuclear Defense Laboratory, October 1966, AD 641843.
18. W.H. Closser, J.M. Swartz, and M.O. Thurston, "Silicon Diode Fast Neutron Dosimeter - Phase III - Reverse-Recovery Lifetime as a Function of Temperature", NDL-TR-83-III, US Army Nuclear Defense Laboratory, October 1966, AD 642582.
19. R.R. Speers, "Silicon Diode Fast Neutron Dosimeter - Phase IV - Determination of the Energy Dependence of the Damage Constant", NDL-TR-83-IV, US Army Nuclear Defense Laboratory, February 1967, AD 648642.
20. J.M. Swartz, W.H. Closser, and M.O. Thurston, "Silicon Diode Fast Neutron Dosimeter - Phase II - Isochronal and Isothermal Anneals of the Radiation Damage", NDL-TR-83-II, US Army Nuclear Defense Laboratory, October 1967, AD 661323.
21. J.M. Swartz and M.O. Thurston, "Analysis of the Effect of Fast-Neutron Bombardment on the Current-Voltage Chracteristic of a Conductivity-Modulated p-i-n Diode", J. Appl. Phys., Vol. 37, No. 2, pp 745-755, 1966.

where: τ_o = initial carrier lifetime

τ = carrier lifetime after irradiation

K = damage constant

ϕ = neutron fluence

D = diffusion constant

L = ambipolar diffusion length

k = Boltzman's constant

T = temperature

e = electron charge

W = width of the base region of the diode.

Equations 1 through 3 relate a diode property (base voltage) to neutron fluence and are taken directly from reference 21 (we note equation 3 is an alternate form of Swartz and Thurston's equation 26).

It is necessary to have a usable relation between observed result and neutron fluence if variation in neutron exposure (possibly 30% on different runs) and variation in response with neutron energy are to be collated. An early result[+] shown in Figure 3 indicated, for a limited range of exposure, a linear change in device forward voltage with neutron exposure. These early results, using diodes identical to those reported here, were obtained with a fixed forward current of 0.1A, but each point was measured after a 20-hour room temperature anneal. Most of the observed voltage change is considered to result from the reduced lifetime in the base and this is assumed to be related to neutron fluence by equation 1. The experimental data of Figure 4[+] clearly implies this relationship. It is noted that figure 4 extends to several-hundred times the fluences used for figure 3, and that the property plotted in figure 4 is the reverse-recovery lifetime.

Annealing plays an important role in measurements of this type and, if annealing depends on neutron energy, an energy dependent behavior might also be time dependent. Anneal curves (30°C) for 3 and 15 MeV neutrons are shown in Figure 5. Note that a very expanded scale has been used, and only the neutron-induced voltage change is shown. At very short times the difference (2 or 3%) may be attributable to the different exposure times needed to obtain the required fluences. The

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[+]The results shown in Figures 3 and 4 were obtained by W.D. Hendricks.

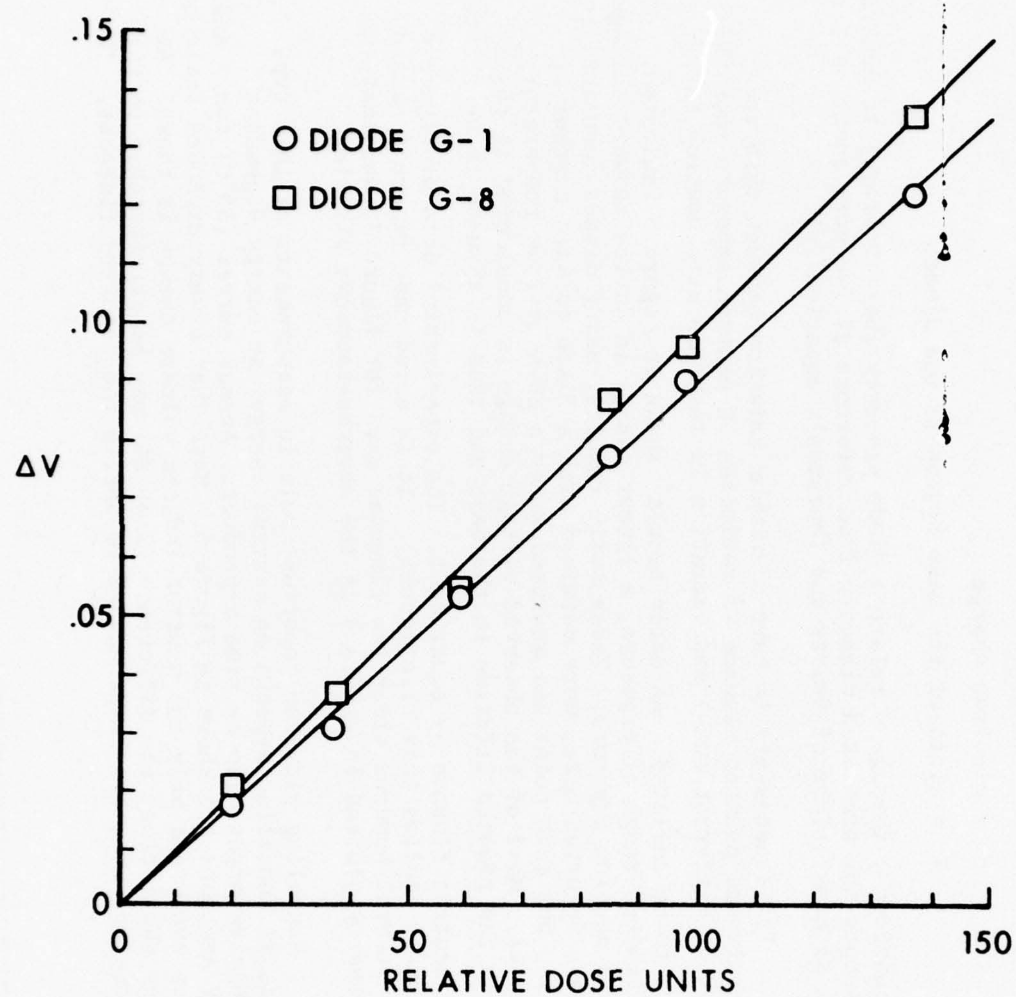

Figure 3. Response of 50-mil Diodes to 3-MeV Neutrons

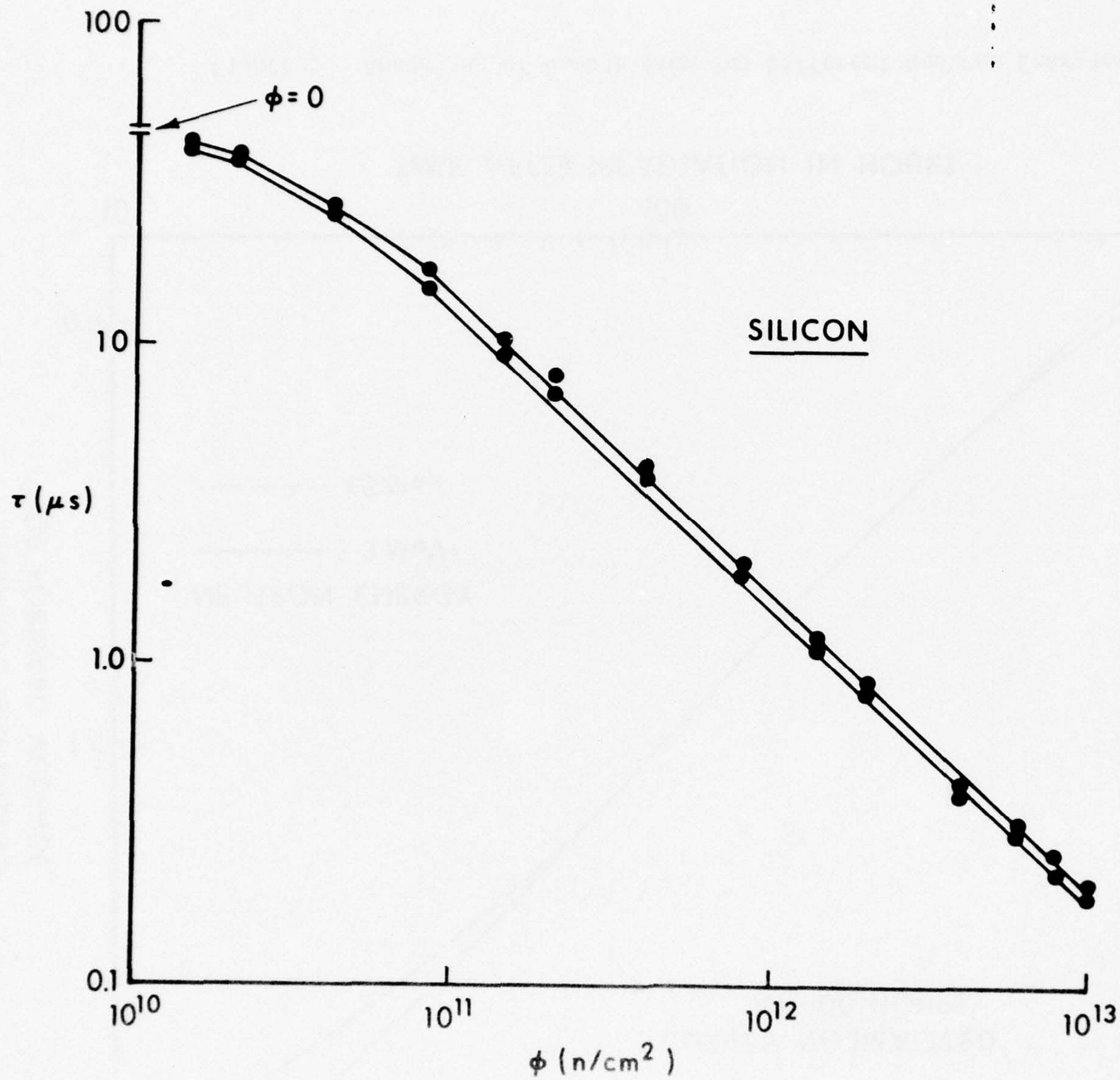

Figure 4. Silicon Diode Reverse-Recovery Lifetime Versus Neutron Fluence

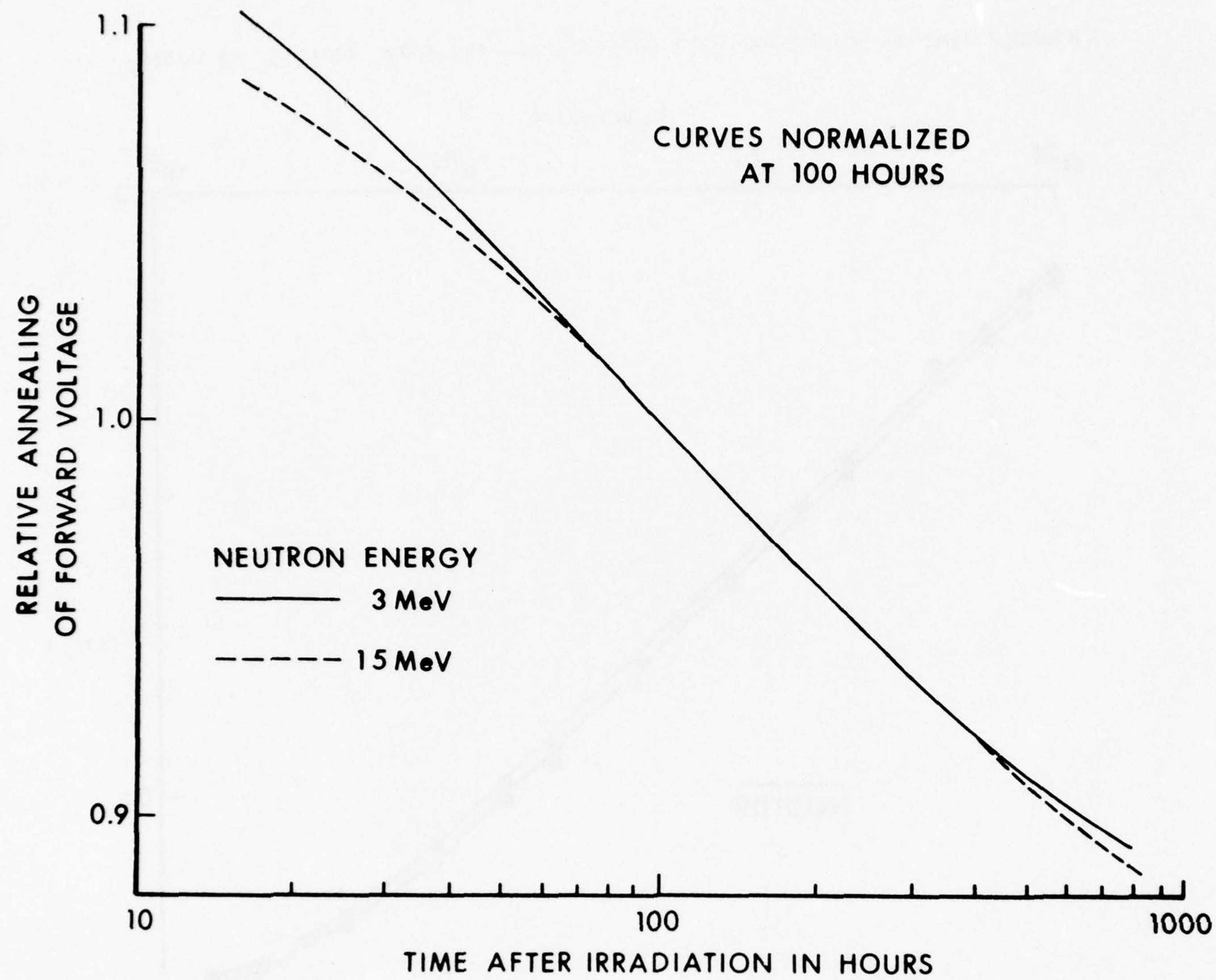

Figure 5. Annealing of Damage from Two Different Neutron Energies

small difference seen at very long times may be due to the formation of some energy-specific defects, or energy-related cluster configurations. There is also the possibility of an unobserved energy-related defect structure that anneals in subsecond time scales. While differences in the anneal curves may be attributed to energy dependence of damage, the similarity of the two anneal curves does not imply that the nature of the neutron-induced damage sites is energy independent. The correct inference is that the annealing process is energy independent and it probably is a single physical process such as the diffusion of the dopant through the lattice to the damage sites. In any case, there is very little energy dependence of annealing that would effect the results sought here. Use of an anneal curve and the choice of a 100-hour after exposure readout time make possible accurate analysis of exposures extending over 1 or 2 days.

Annealing due to carrier injection has been noted by Barnes[22] and by Mallon and Harrity[23]. This effect is due to the breakup of neutron-induced clusters and an apparent increase in the number of divacancies. Although it has not been possible to measure this anneal, the consistency of the temperature, the injection level, the length of time current is injected to obtain an accurate reading, and the number of times a diode is read to obtain the 100-hour value all contribute to an assurance that injection annealing is consistent (and not a factor in the ratio of damage at different energies). In a similar way, the suggestion by Bolotov, et al.[24], that the variety of data on radiation defect formation in semiconductors showing discrepancies in results from different researchers is due to differences in experimental conditions during irradiation, has not been investigated specifically. Following most other investigators, it is assumed that establishment of an equilibrium condition after irradiation, at a temperature significantly higher than that during irradiation, is sufficient to eliminate prior thermal history as a factor in the number and nature of permanent defects.

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22. C.E. Barnes, "Thermal and Injection Annealing of Neutron-Irradiated P-Type Silicon Between 76°K and 300°K", IEEE Trans. Nucl. Sci., Vol. NS-16, No. 6, pp 28-32, 1969.
23. C.E. Mallon and J.W. Harrity, "Short-Term Annealing in Transistors Irradiated in the Biased-Off Mode", IEEE Trans. Nucl. Sci., Vol. NS-18, No. 6, pp 45-49, 1971.
24. V.V. Bolotov, A.V. Vasiljev, V.I. Panov, and L.S. Smimov, "Influence of Irradiation Conditions on the Accumulation and Properties of Radiation Defects", Inst. Phys. Conf. Ser, No. 23, pp 240, The Institute of Physics, London and Bristol, 1975.

Procedurally, to determine the energy-dependence of diode response, an initial exposure of 10^{11}-14 MeV neutrons/cm^2 was used to place the diodes in a range where damage effects are dominated by neutron exposure rather than material purity and fabrication history. The diodes were then annealed overnight at 50°C and allowed to stabilize at least one week before use. The diodes, in sets of three, were exposed to neutrons of some particular energy and were maintained at 30°C after exposure in order to control annealing. Following exposure, the forward voltage was measured at selected times for one week and the value at 100 hours after the mid-exposure-time was used. After an experiment the diodes were annealed for several hours at 200°C and were then ready for further use at near-original condition.

IV. DAMAGE CALCULATIONS

Damage calculations to compare with experimental results were desired and there was a particular Army interest in a simple damage model which would permit investigation of the sensitivity of damage calculations to the details of neutron cross sections. To this end a computer program was prepared that will accept coefficients for a Legendre polynomial fit to the angular distribution of a partial cross section, determine the silicon recoil energy, and calculate the Lindhard fraction of energy for displacement damage. The program iterates through 60, 3-degree intervals, finds the appropriate solid angle in each case, forms the product of solid angle, recoil energy, differential cross section, and displacement fraction, and sums the 60 contributions. The Lindhard fraction and the assumption that a constant fraction of the displacement energy is uniformly effective in creating permanent damage are, with the neutron cross sections, the uncertain factors in the calculations.

The neutron cross sections were taken from the work of Grimes[25], Kinney and Perey[26], Dickens[27], Nellis and Buchanan[28], and Velkley et al.[29].

25. S.M. Grimes, "Fluctuations in the Neutron Cross Sections of Si", Nuclear Physics, Vol. A124, pp 369-392, 1969.
26. W.E. Kinney and F.G. Perey, "Neutron Elastic- and Inelastic-Scattering Cross Sections for Si in the Energy Range 4.19 to 8.56 MeV", ORNL-4517, Oak Ridge National Laboratory, July 1970.
27. J.K. Dickens, "^{28,30}Si(n,xγ) Reaction for $5.3 \leq E_n \leq 9.0$ MeV", ORNL-TM-2883, Oak Ridge National Laboratory, February 1970.
28. D.O. Nellis and P.S. Buchanan, "Neutron Scattering and Gamma-Ray Production Cross Sections for N, O, Aℓ, Si, Ca, and Fe", DNA 2716, Defense Nuclear Agency, February 1972.
29. D.E. Velkley, D.W. Glasgow, J.D. Brandenberger, M.T. McEllistrem, J.C. Manthuruthil, and C.P. Poirier, "Scattering of 9.0 MeV Neutrons by Aℓ, Si, Fe, Ni, and Co", Phys. Rev. C., Vol. 9, pp 2181-2192, 1974. (A preprint of this work, including Legendre polynomial fits to elastic data at 8.5 and 9.0 MeV, was kindly supplied by Dr. H.J. Hennecke).

Differential elastic scattering distributions for neutron energies of 8.55 and 9.0 MeV are shown in Figure 6. It may be noted that the anisotropy covers two orders of magnitude and, also, that the distribution can change significantly for a small change in neutron energy. Figure 7 shows the angular distributions for inelastic scattering to the first excited state, for the same energies shown in Figure 6. Again there is a considerable change with neutron energy; however, the anistropy is only about a factor of two. Most other neutron reactions in silicon are thought to be more isotropic.

The Lindhard fraction for displacement damage was evaluated using the stopping-power theory of Lindhard, Scharff, and Schiott (LSS) [30]. Rather than the approximation to LSS previously cited[1], the calculations were done using an empirical fit to LSS taken from Bertin, et al.[31].

The first calculations, serving to check procedures and their efficacy, are shown in Table I. The table gives the elastic and first-excited-state inelastic results for six angular-distribution/neutron-energy combinations (five neutron energies). The cross sections were take from ARL[29] and ORNL[26], and the Legendre polynomial coefficients supplied by the authors were used. Damage for an isotropic angular distribution with the same net cross section is shown in each case. The inelastic L-5 fits produce results that differ only slightly from those of an isotropic distribution. The second and third rows in Table I show results for two different angular distributions for the same neutron energy. If it is assumed that one distribution is correct, then, the table shows that a wrong (but reasonable) elastic distribution can produce a 10% error. Of greater importance, the L-8 fits for elastic angular distributions produce only about half as much damage as would be obtained if the reactions were isotropic. This is in good agreement with the observations of Stein[13], based on very limited cross section information. This can be understood from Figure 8. The large curve, showing damage for an isotropic distribution, is shaped by the available solid angle and the skewness is a result of the recoil energy and the Lindhard fraction. Both of the angular distributions place a significant part of the cross section at forward angles where the damage is small.

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30. J. Linhard, M. Scharff and H.E. Schiott, "Range Concepts and Heavy Ion Ranges", Kgl. Danske Videnskeb Selskab, Mat.-Fys. Medd., Vol. 33, No. 14, 1963, pp 1-42.
31. M.C. Bertin, N. Benczer-Koller, G.G. Seaman, and J.R. MacDonald, "Electromagnetic Transition Rates in ^{58}Ni", Phys. Rev. Vol. 183, pp 964-977, 1969.

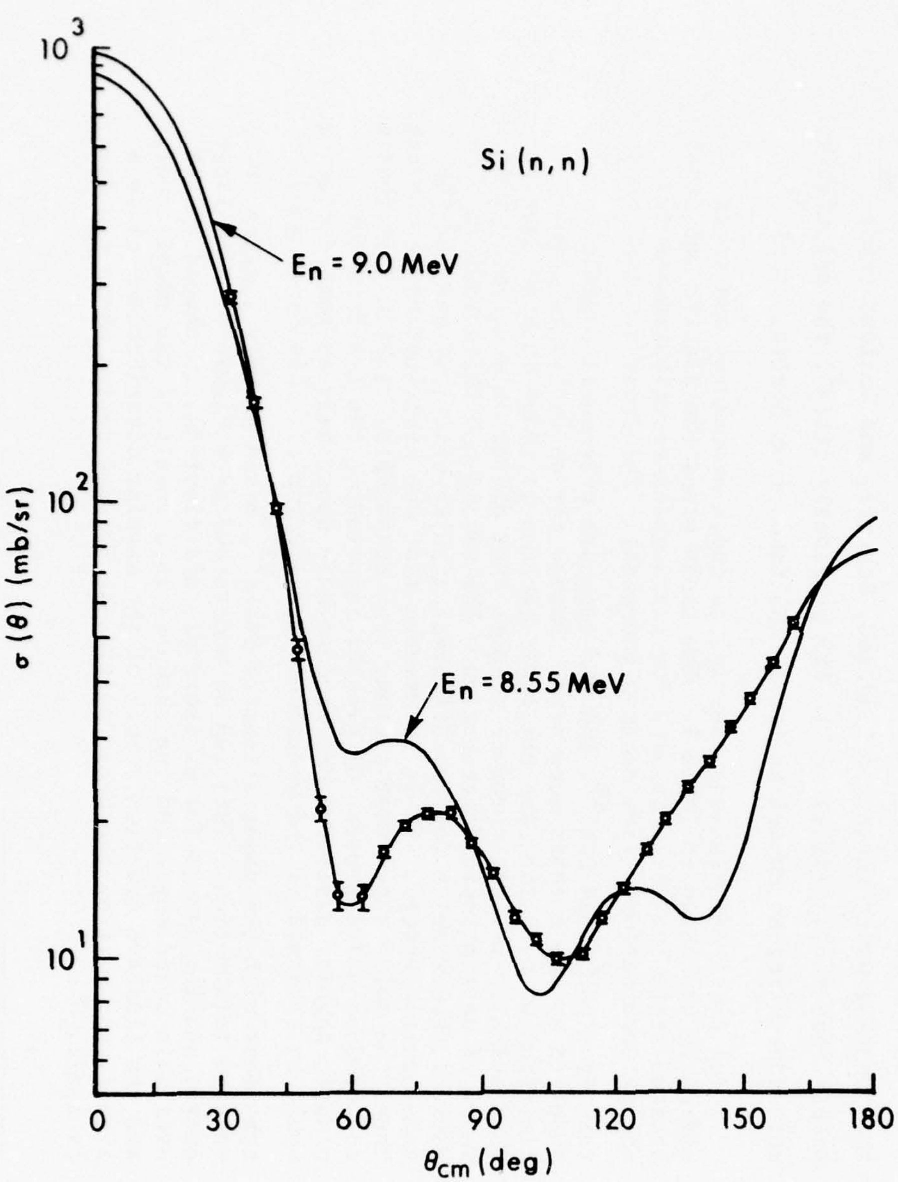

Figure 6. Silicon Differential Elastic Scattering at 8.55 and 9.0 MeV

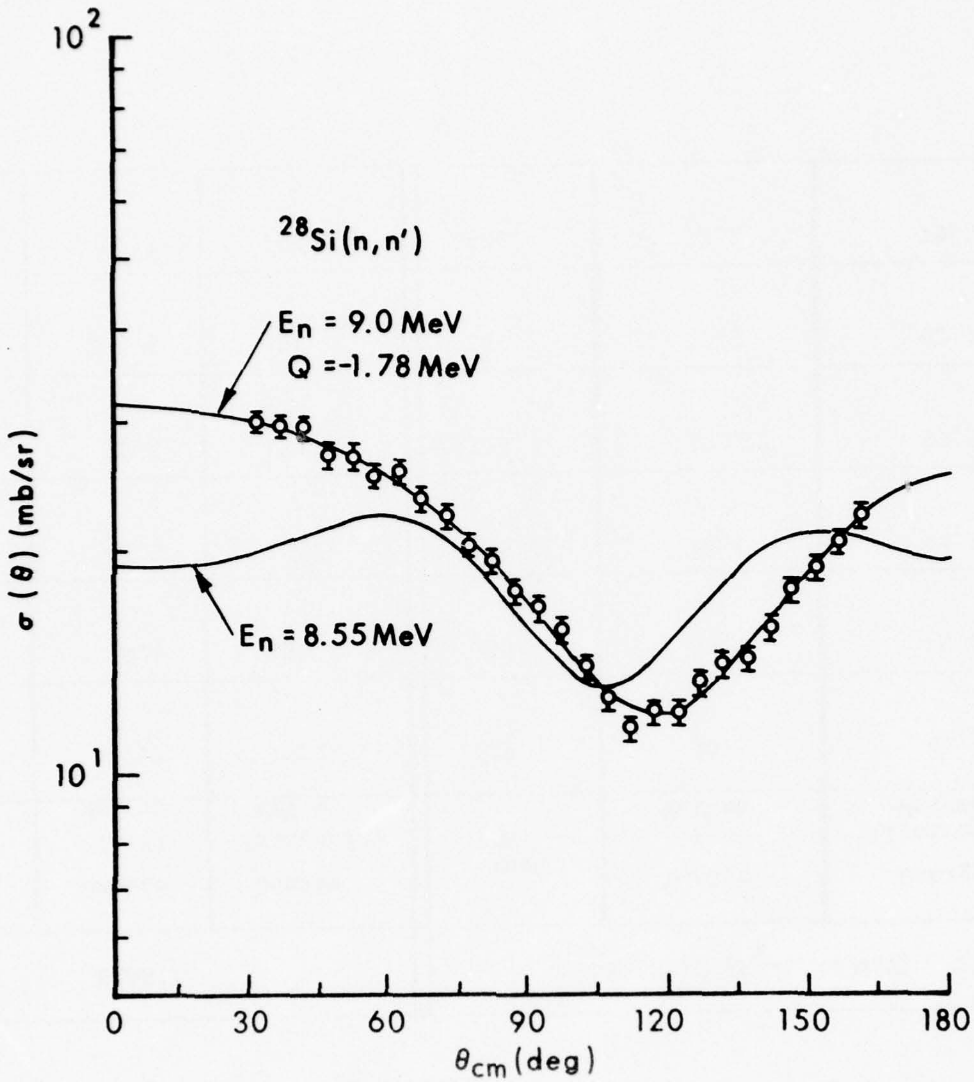

Figure 7. Silicon Inelastic Scattering to the First Excited State

TABLE I. SILICON DAMAGE, Preliminary Calculations

	ELASTIC			INELASTIC (E_x=1.78 MeV)		
E_N MeV	σ_{el} (mb)	Damage (L-8) MeV· mb	Damage (Isotropic) MeV· mb	σ_{inel} (mb)	Damage (L-5) MeV· mb	Damage (Isotropic) MeV· mb
9.00 (ARL)	848.	71.7	161.2	249.	40.5	45.1
8.55 (ARL)	838.	70.6	155.7	230	39.4	40.6
8.55 (ORNL)	883.	63.3	164.1	25.4	44.1	44.8
7.55 (ORNL)	905.	76.8	158.8	323.	58.5	53.3
6.37 (ORNL)	1,244.	103.4	201.1	549.	77.9	82.1
5.44 (ORNL)	1,087.	92.8	162.2	586.	73.2	79.3

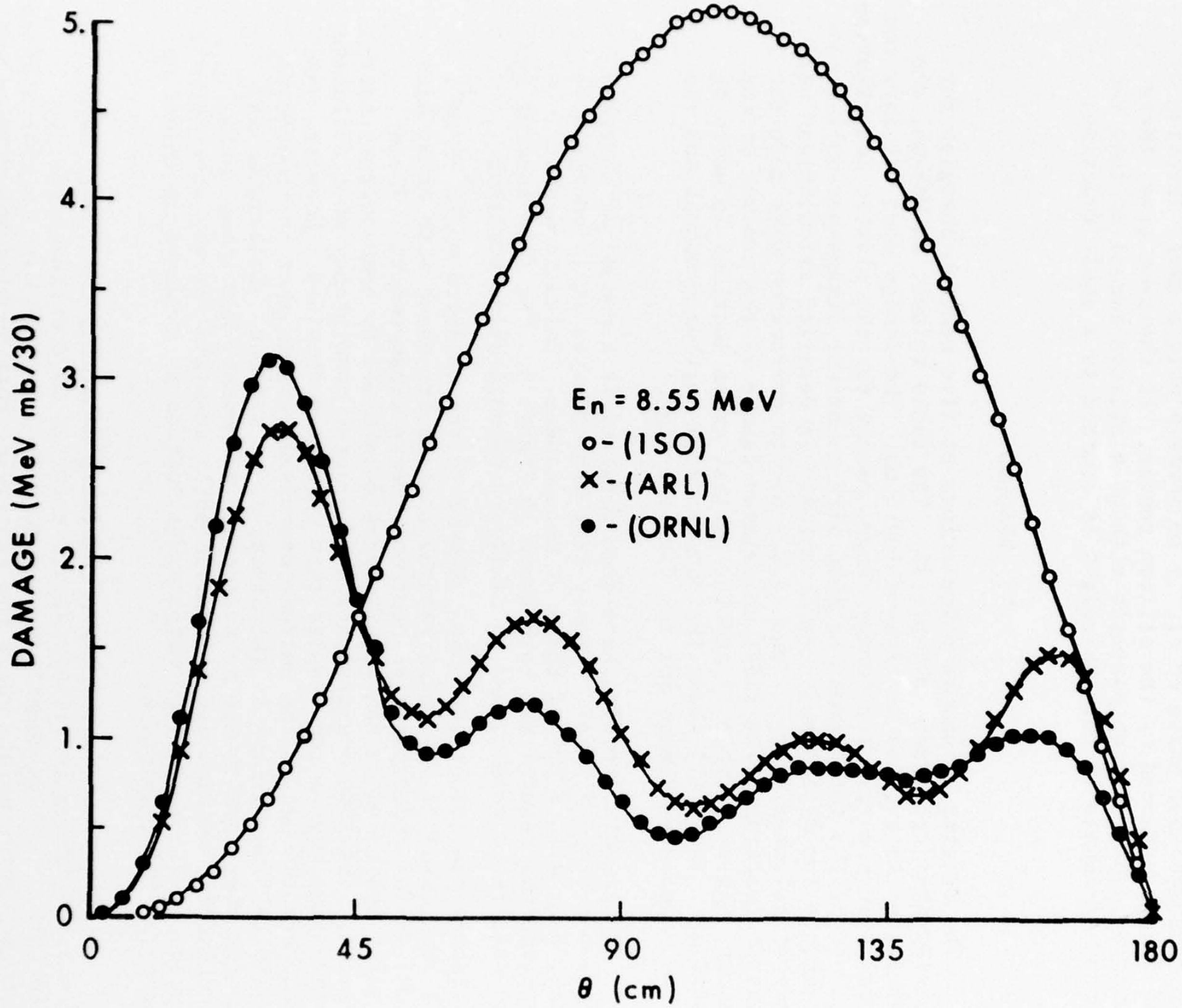

Figure 8. Silicon Damage from Elastic Scattering

The calculations have been carried out, in the same detail, for the several reactions that occur and to several excited states for each reaction. All reactions except elastic and first-excited-state inelastic were taken as isotropic. Also, only damage from the silicon recoil was calculated. The light reaction particle (proton or alpha) can be shown (see Smith et al.[12]) to produce only a small fraction of the damage produced by the silicon recoil. At the same time, there is never a light reaction particle without a silicon recoil so that the amount of damage in this oversight is limited to a small fraction.

V. RESULTS

The results of damage calculations at five neutron energies for 15 reactions are shown in Table II. The table values, in MeV-mb, are normalized to a cross section of 100.5 mb. The damage does not vary too greatly in a particular energy range, except for the elastic contribution, and use of the total cross section with a nominal damage-per-unit-cross-section value would thus seem acceptable if detailed calculations were made at selected energies and if a separate correction were made for the elastic fraction. The final calculated damage is the product of the results shown in Table II and the partial cross sections in units of 100.5 mb. Table III shows the damage cross-section products and the total calculated damage for the five energies.

Experimental results have been obtained at a number of energies between 5.6 and 9.8 MeV. Twenty-five measurements at 19 energies were made, each with a set of three or more diodes. Calculated and experimental results are both shown in Figure 9. The five squares are the calculated results and an arbitrary normalization constant (relating the calculated units, MeV-mb to the measured $mV/10^9\text{-}n/cm^2$) has been assumed. The experimental results are shown with error bars based on the uncertainty in neutron fluence measurements. These results are based on neutron fluences determined by beam-current integration. The same measurements have greater consistency when evaluated with sulfur activation results that were also obtained. However, some structure is seen in the sulfur-determined results that is thought to be due to fluctuations in the S(n,p) cross section. Calculated and experimental results are in reasonable agreement, but these early experimental results are not sufficiently accurate for any more definitive conclusions. The silicon total cross section is shown as an insert on Figure 9, for comparison.

Initial plans were to experimentally determine the energy dependence of neutron damage in silicon at all energies in contiguous energy intervals. It subsequently seemed more important to make careful measurements at energy points where the available cross section information would permit detailed calculations. As a start on this, the large fluctuation

TABLE II. SILICON DAMAGE FOR 100.5 mb CROSS SECTIONS

Reaction	E_{loss}	E_n 9.0 MeV	8.55 MeV	7.55 MeV	6.37 MeV	5.44 MeV
Elastic, ϕ	0	8.43	8.42	8.45	8.28	9.49
(n,n'), ϕ	1.78	16.2	17.0	18.0	14.1	12.4
Elastic(ISO)	0	18.9	18.5	17.5	16.6	14.8
(n,n')	1.78	18.0	17.5	16.4	14.8	13.4
(n,α_o)	2.65	21.0	20.6	19.4	17.6	15.8
(n,α_1)	3.23	20.5	19.9	18.6	16.6	14.5
(n,α_2)	3.63	20.0	19.5	18.0	15.9	13.6
(n,p_{0+1})	3.85	16.7	16.2	15.0	13.3	11.7
(n,α_3)	4.26	19.3	18.7	17.1	14.6	12.0
(n,α_4)	4.61	18.9	18.2	16.5	13.9	11.1
(n,n')	4.80	16.7	16.2	14.8	12.9	11.2
(n,p_{2+3})	4.85	16.2	15.7	14.4	12.6	10.9
(n,α_5)	5.21	18.0	17.3	15.4	12.4	9.3
(n,p_4)	5.23	16.1	15.5	14.2	12.4	10.6
(n,n')	6.80	15.7	15.1	13.6	0	0

TABLE III. SILICON DAMAGE
(MeV - mb)

	E_n				
Reaction	9.0 MeV	8.55 MeV	7.55 MeV	6.37 MeV	5.44 MeV
Elastic	71.5	70.6	76.5	94.7	88.9
(n,n') (1.78)	47.3	40.3	53.0	73.9	75.7
(n,α_o)	24.2	24.7	19.4	0.5	0.2
(n,α_1)	5.1	5.0	6.0	0	0
(n,α_2)	8.0	6.8	2.7	0	0
(n,P_{o+1})	9.5	13.4	22.5	31.3	9.4
(n,α_3)	4.8	3.7	0.9	0	0
(n,n') (4.80)	15.9	16.8	17.3	18.6	3.4
(n,P_{2+3})	6.5	4.7	7.5	0	0
(n,n') (6.80)	63.6	44.1	8.8	0	0
Other	36.1	30.0	31.6	0	0
TOTAL	292.5	260.1	246.2	219.0	177.6

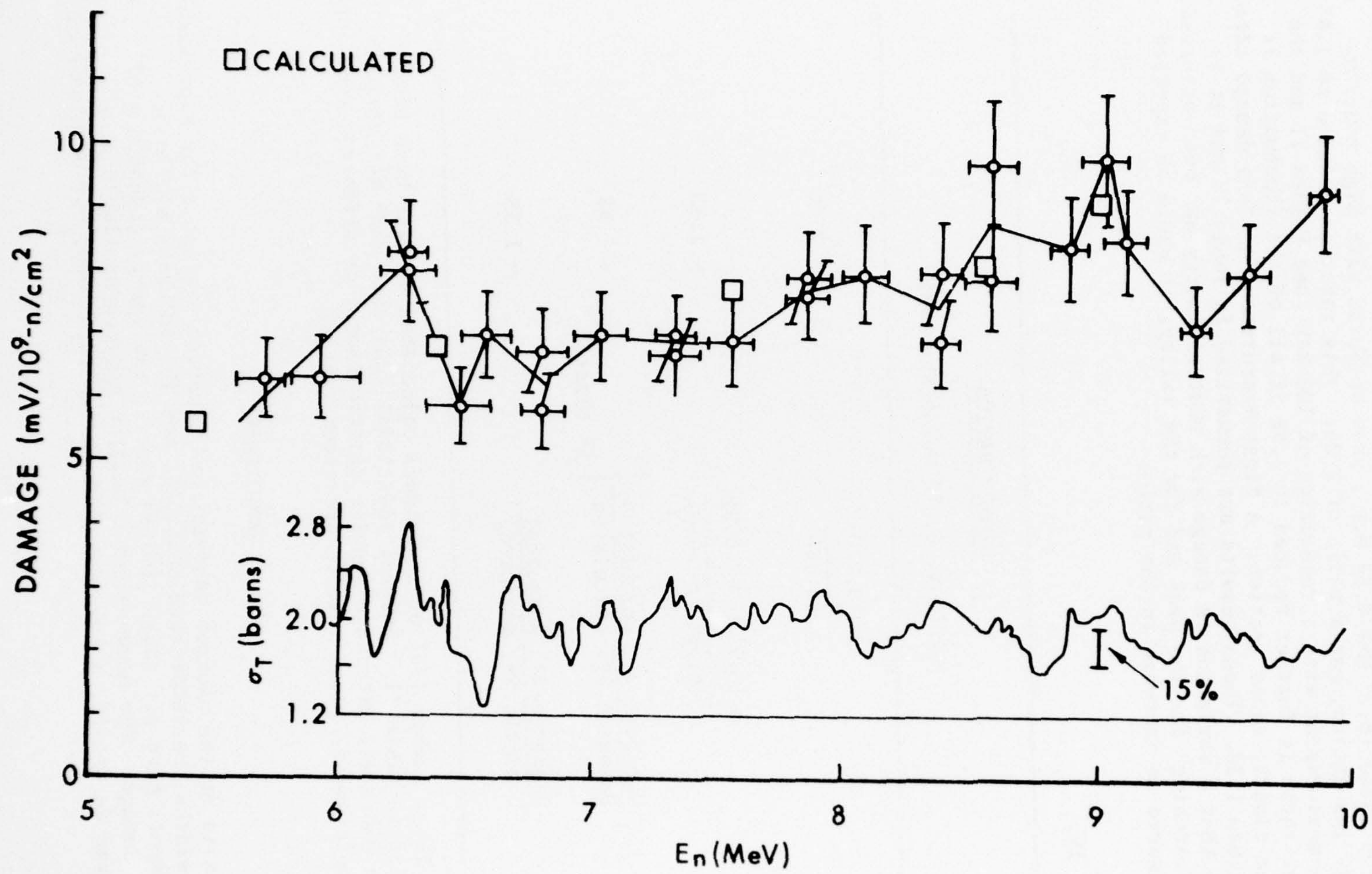

Figure 9. 6- to 10-MeV Neutron Damage in Silicon

in total cross section shown in Figure 1 was chosen. The total cross section ratio (6.27 MeV/6.59 MeV), when measured with high neutron-energy resolution, has a ratio of 2.26. This ratio is reduced to 1.83 for a measurement with a resolution of 100 keV (see Figure 1) and the damage ratio is further reduced to 1.58 if all of the fluctuation is in the elastic cross section. A first measurement of this damage ratio has given 1.38. These results are summarized in Table IV and it is clear that a variation in damage with neutron energy has been observed. By "searching" for the peak and for the valley, it would be expected to observe an increase in the ratio.

TABLE IV.

DAMAGE RATIOS

(SILICON, 6.270 MeV/6.586 MeV)

$\frac{\sigma_T(6.270)}{\sigma_T(6.586}$		= 2.26
$\frac{\sigma_T(6.270 \pm .050)}{\sigma_T(6.586 \pm .050)}$		= 1.83
$\frac{\text{Damage}(6.27,\ \text{calculated})}{\text{Damage}(6.59,\ \text{calculated})}\Bigg\vert$	$\delta\sigma$ elastic	= 1.58
$\frac{\text{Damage}(6.27,\ \text{measured})}{\text{Damage}(6.59,\ \text{measured})}$		= 1.38

A large number (75) of individual calculated results have been presented in Table II. Several additional runs were made for various neutron energies, alternate angular distributions, or different reactions. For completeness, these results are given Table V.

VI. CONCLUSIONS

Limits on the neutron energies and fluences available for experiments, energy widths, backscattered neutrons, and the accuracy of fluence measurements have seriously limited work on the energy dependence of neutron damage. The monoenergetic neutron sources available at a Tandem Van de Graaff, a low-mass neutron exposure room, use of wide-base

TABLE V. ADDITIONAL DAMAGE CALCULATIONS

Neutron Energy (MeV)	Reaction	Energy Loss (MeV)	Angular Dist.	Damage* (MeV - mb)
14.	Elastic	0.0	Iso	22.0
10.	"	"	"	19.3
4.5	"	"	"	13.2
3.5	"	"	"	11.45
2.5	"	"	"	9.295
1.65	"	"	"	6.997
1.037	"	"	"	4.93
0.805	"	"	"	4.02
0.450	"	"	"	2.45
0.219	"	"	"	1.266
0.158	"	"	"	0.929
0.103	"	"	"	0.616
14.	(n,α)	0.0	"	24.53
"	"	- 0.580	"	24.24
"	"	- 0.980	"	24.02
"	"	- 1.610	"	23.67
"	"	- 2.560	"	23.09
"	"	- 5.00	"	21.28
"	"	- 8.00	"	18.37
10.	"	0.0	"	21.95
"	"	- 0.58	"	21.46
"	"	- 0.98	"	21.09
"	"	- 1.61	"	20.48
"	"	- 2.56	"	19.44
"	"	- 5.00	"	16.13
14.	(n,p)	0.0	"	20.85
"	"	- 1.00	"	20.56
"	"	- 1.378	"	20.45
"	"	- 3.00	"	19.99
"	"	- 5.00	"	19.43
"	"	- 8.00	"	18.63

*Damage is in MeV-mb, but for a total cross section for the specified reaction of 100.5 mb.

TABLE V. (Continued)

Neutron Energy (MeV)	Reaction	Energy Loss (MeV)	Angular Dist.	Damage* (MeV-mb)
10.	(n,p)	0.0	Iso	17.72
"	"	- 1.00	"	17.30
"	"	- 1.378	"	17.14
"	"	- 3.00	"	16.46
"	"	- 5.00	"	15.65
14.	(n,n′)	- 1.78	"	22.22
10.	"	"	"	19.18
4.5	"	"	"	11.93
3.5	"	"	"	9.76
2.5	"	"	"	7.02
14.	"	- 4.80	"	21.28
10.	"	"	"	17.83
14.	"	- 6.80	"	20.67
10.	"	"	"	16.94
14.	"	-10.0	"	19.71
0.103	Elastic	0.0	L-1	0.631
0.158	"	"	"	0.966
0.219	"	"	"	1.241
0.450	"	"	"	2.333
0.805	"	"	L-3	3.746
1.037	"	"	"	3.314
1.65	"	"	L-4	5.518
2.50	"	"	L-6	6.233
4.50	"	"	"	7.543
5.50	"	"	"	8.523
7.50	"	"	L-7	8.228
9.00	"	"	L-8	8.596
10.0	"	"	L-11	8.942
12.0	"	"	L-9	9.513
14.0	"	"	L-14	9.758

* Damage is in MeV—mb, but for a total cross section for the specified reaction of 100.5 mb.

conductivity-modulated silicon diodes, and very-precise voltage measurements (reflecting changes in the injected carrier lifetime) have been combined to provide a capability for a detailed experimental evaluation of the energy dependence of neutron damage in silicon.

To compare experimental results with calculations using the most recent neutron cross section data, a computer program has been prepared that accepts coefficients for a Legendre polynomial fit to a partial cross section, determines the silicon recoil energy at a particular angle, and calculates the Lindhard fraction of energy for displacement damage. In addition to providing a comparison base for experimental results, the calculated results provide a direct indication of the effect of angular distributions and the sensitivity of damage calculations to various details of the input neutron cross sections. The order of importance of these cross section details has been found to be: correct total cross section; elastic fraction; elastic angular distribution; and variations in angular distributions at resonances or fluctuations.

A number of directions for future work are clear from the above. Measurements of damage at other neutron energies and a program that will calculate damage at all neutron energies using as input a tape from one of the cross section libraries are among the most obvious directions. These tasks have been completed recently and work is being initiated to prepare reports. In view of these reports to be prepared, future work will not be discussed further here.

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